Spot propagation characteristics in laterally strained boundary layers

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Spot Propagation Characteristics in Laterally Strained Boundary Layers

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Abstract Owing to the importance of the spot propagation characteristics in transition zone modeling, the effect of lateral streamline convergence alone on the spot propagation characteristics has been studied. It is found that for the extent of lateral straining introduced here, the two- dimensional spot propagation characteristics are unaffected.

Introduction

Following Emmons' (1951) spotwise transition theory, turbulent spot in two-dimensional (2-D) boundary layers have extensively been studied in the past (Schubauer and Klebanoff 1955; Wygnanski et al. 1976; Cantwell et al. 1978; Gad-el-Hak et al. 1981; Gutmark and Blackwelder 1987; Gostelow et al. 1992, to name a few). A turbulent spot is an island of turbulence moving with fixed front and rear velocities in a laminar surrounding. The propagation characteristics of a spot are important in modeling the transition zone. In contrast to idealized 2-D flows, flows in general involve lateral streamline convergence/divergence, longitudinal streamline curvature, etc. A lateral streamline convergence/divergence causes an additional strain rate to a nominally 2-D flow and may influence the spot propagation characteristics. Recent investigations by Jahanmiri et al. (1996) in a constant pressure diverging flow, however, does not show any significant change in the spot propagation characteristics from those in 2-D constant pressure flows. A laterally converging streamline flow has a thicker boundary layer (Vasudevan 2000), and since a thicker boundary layer in 2-D adverse pressure gradient flows influences the spot propagation characteristics (Gostelow et al. 1992; Van Hest 1996), one may expect some effect of converging streamlines on the spot propagation characteristics. Recently, Panchapakesan et al. (1997) have studied the effect of lateral streamline convergence on turbulent flows and observe a large reduction in the skin friction value. In terms of a non-dimensional parameter characterizing the effect of streamline convergence/divergence, Panchapakesan et al. point out that, unlike a diverging flow, a converging flow may not attain an equilibrium turbulent state. It therefore seems worthwhile to study the effect of lateral streamline convergence on the turbulent spot propagation characteristics, as reported in this paper.

Experimental details

Experiments were carried out in a low-speed and low- turbulence open-circuit wind tunnel at the Department of Aerospace Engineering, Indian Institute of Science. A constant pressure converging streamline flow is achieved by converging the side walls at about 10° (which is approximately the half angle of the spot envelope) and di- verging the tunnel roof appropriately such that a constant cross-sectional area is maintained throughout the test section, as shown in Fig. 1; x is the streamwise distance, z is the spanwise distance, y is normal to the $x - z$ plane. It may be mentioned that the flow convergence is nearly the same as in the experiments of Panchapakesan et al. (1997). Since the converging channel for the present study has replaced the original square test section, an additional contraction is provided for smooth entry of the flow into the test section. An aluminum flat plate (Fig. 1) on which the measurements are made forms the base of the con- verging channel test section. The flat plate has an elliptical leading edge to prevent separation at the leading edge. In order to have a thicker boundary layer in the converging section, the convergence is preceded by a flat region of 8 cm (Fig. 1).

Loudspeaker-driven artificial turbulent spots are introduced through a 0.05 cm hole located on the plate at $x_s = 13.5\ cm$ from the leading edge. A low-frequency oscillator providing a square wave output controls the frequency (5 Hz) of the pulse.

A constant temperature hot-wire anemometer with a Wollaston process wire 5 micron in diameter (length-to- diameter ratio is about 800) is used to measure the velocity signal. As the signal acquisition rate is 2 kHz (using a 12-bit data acquisition board), about 50 spots are collected during the 10-s sampling time used in the experiment.

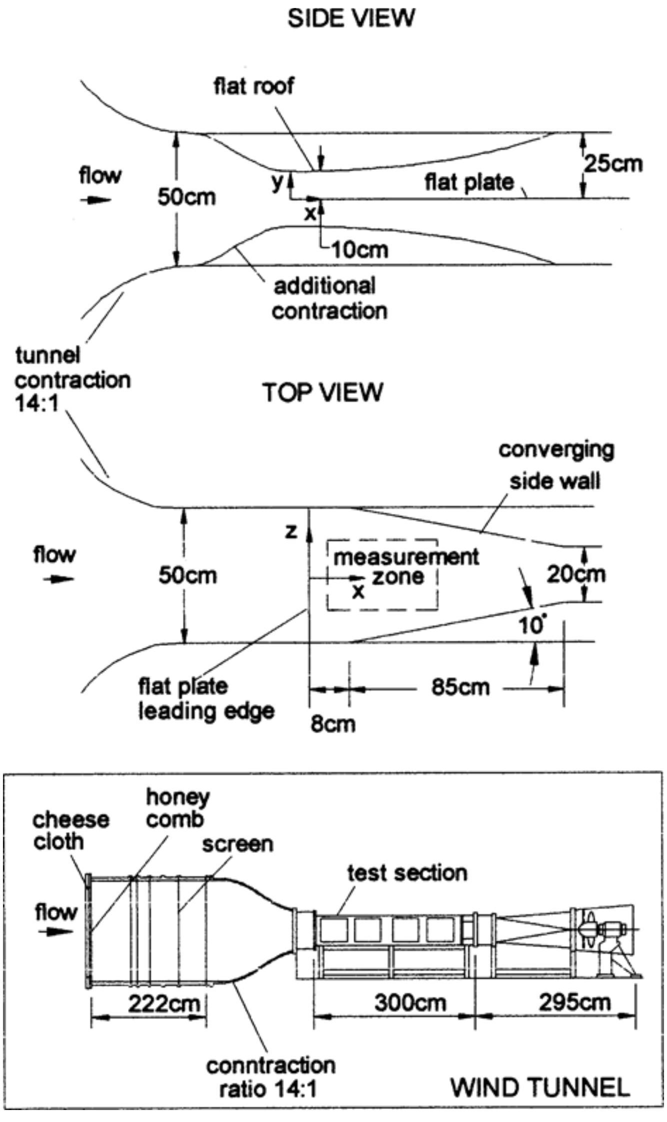

Fig. 1. The flow geometry; *inset* - wind tunnel

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The spot detection technique is the same as the intermittency detection technique of Ramesh et al. (1996). The velocity signal ($e^{'}$) is sensitized by double differentiating, ($D = d^2e^{'}/dt^2$) and then squaring it; t denotes the time. A probability density plot of the sensitized signal is constructed in order to infer the threshold (Th), which is then used to discriminate between the turbulent and non-turbulent parts of the signal. The intermittency function $I(t)$ is then defined as, $I(t) = 0$ for D^2 >Th, and $I(t) = 1$ for D^2 > Th. A typical spot signal, its D^2, the corresponding $I(t)$, and trigger pulses are shown in Fig. 2.

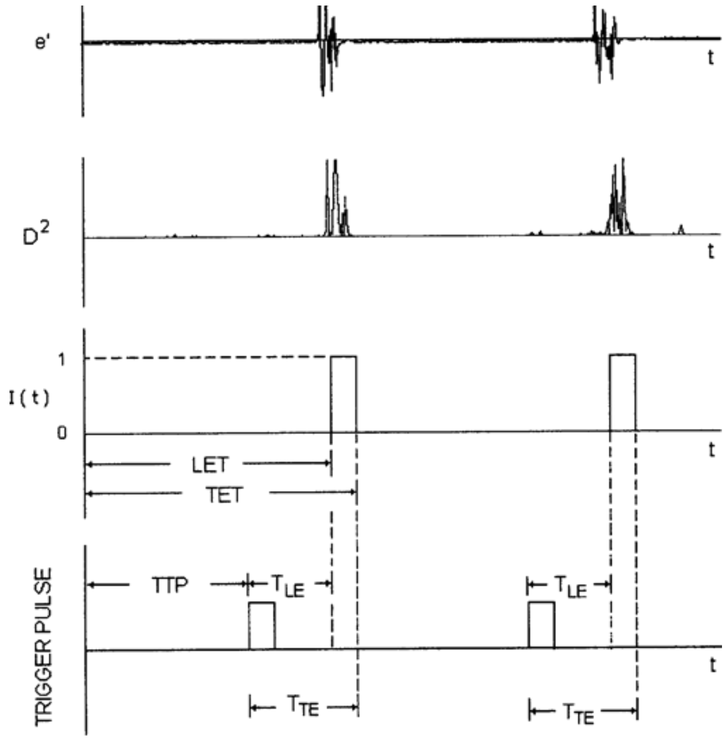

Fig. 2. Time series of raw signal, D^2, $I(t)$, and trigger pulse

The measurements are made at seven x-stations and at various spanwise locations (at an interval of $\Delta z = 0.5\ cm$), in order to cover the spot envelope in the $x - z$ plane. The hot wire was placed at a height of $y \approx 0.5\ cm$ corresponding to about 20% of the laminar boundary layer thickness at x_s (Gutmark and Blackwelder 1987). The leading edge and trailing edge times of the spots are measured with respect to the leading edge of the trigger pulse corresponding to each spot. As shown in Fig. 2, the leading edge and trailing edge times are $T_{LE} = LET - TTP$ and $T_{TE} = TET - TTP$, respectively. The phase average (or ensemble average) of a large number of spots are used to estimate T_{TE} and T_{LE}.

Results and discussion

The measurements reported here are made at a free- stream velocity of $U = 10.3\ m/s$. Both the streamwise and spanwise pressure distributions in the test section are found to be constant (Vasudevan 2000). A laterally di- verging/converging flow is an interesting one in the sense that this 3-D flow, under the source/sink approximation of Kehl (1943), reduces to a 2-D flow by means of the Mangler transformation, as shown by Ramesh et al. (1997). The measured laminar base flow therefore compares well with the Blasius flow, as shown in Fig. 3. The leading and trailing edge spot celerities are shown in Fig. 4. It can be seen that the spot origin is not exactly at the spot source x_s. Instead, the virtual origin of the spot is at $x_0 = -3.04\ cm$. The leading and trailing edge velocities obtained in the present case are $U_{LE} = 0.88U$ and $U_{TE} = 0.65U$, respectively. The leading edge velocity agrees well with the 2-D constant pressure value of $U_{LE} \approx 0.87U \rightarrow 0.89U$ (e.g., Schubauer and Klebanoff 1955; Wygnanski et al. 1976; Cantwell et al. 1978; Gutmark and Blackwelder 1987). However, the trailing edge velocity is slightly higher than the generally accepted value of $0.5U$ for 2-D flows (e.g., Schubauer and Klebanoff 1955; Wygnanski et al. 1976; Cantwell et al. 1978). The higher trailing edge velocity can be attributed to the low Reynolds number effect, as observed by Wygnanski et al. (1982).

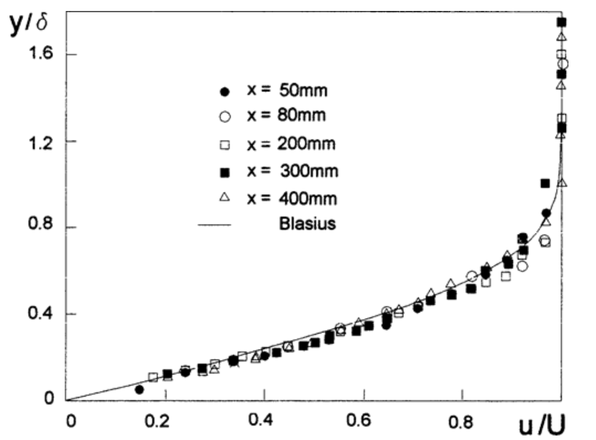

Fig. 3. Laminar base flow compared with the Blasius flow

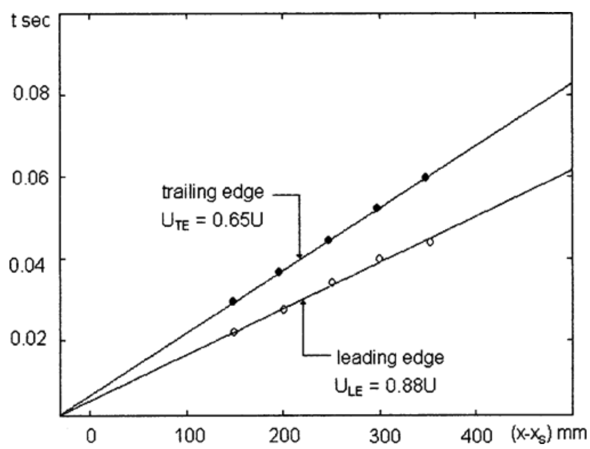

Fig. 4. Spot celerities; x_s is the spot source location (Re_{δ^*} at x_s is 460)

These authors report that when the Reynolds number based on the displacement thickness (Re_{δ^*}) at x_s is varied from 500 to 1,500, the trailing edge celerity reduces from $0.62U$ to $0.5U$. In the present measurements, the value of Re_{δ^*} at x_s being 460, the faster trailing edge is attributed to the low Reynolds number effect. Therefore, the leading and trailing edge celerities are the same as in 2-D constant pressure flows. Figure 5 shows the spot shapes at different instants of time. It can be seen that the spot growth is contained within the conical envelope of the included angle 22°. This spot spread angle compares well with the value of 22.6° reported by Schubauer and Klebanoff (1955) in a 2-D constant pressure flow. Interestingly, Jahanmiri et al. (1996) also find about the same spot spread angle in a constant pressure diverging flow. It can be seen in Fig. 5 that the spots are self-similar in nature (Coles and Barker 1975; Wygnanski et al. 1976; Van Hest 1996); the 30-ms spot seems to be less developed, but it is self-similar in the conical coordinates mentioned below. In the light of the above-mentioned similarities with a 2-D flow, we also look for the conical similarity of Cantwell et al. (1978) in terms of the coordinates, $x_c = (x - x_0)/U(t - t_0)$, $y_c = y/U(t - t_0)$, $z_c = z/U(t - t_0)$, where x_0 is the virtual origin of the spot, and t_0 is the time corresponding to the virtual origin. As shown in Fig. 6, the self-similar structure is quite evident. For 2-D flows, similar observations were made by Cantwell et al. (1978) and Van Hest (1996). Thus, the extent of lateral straining introduced here does not seem to affect the overall spot propagation characteristics. The effect of large convergence on the spot propagation characteristics, however, remains to be studied. Since only the overall spot propagation characteristics are sufficient for aiding the transition zone modeling, we have not looked into the internal structure of the spot, and such results will be reported separately.

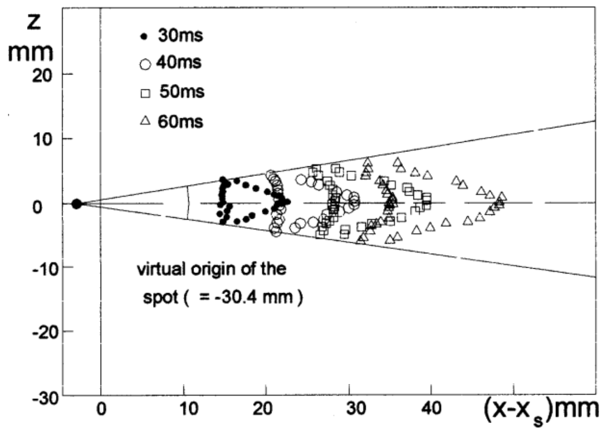

Fig. 5. Spots at various instants

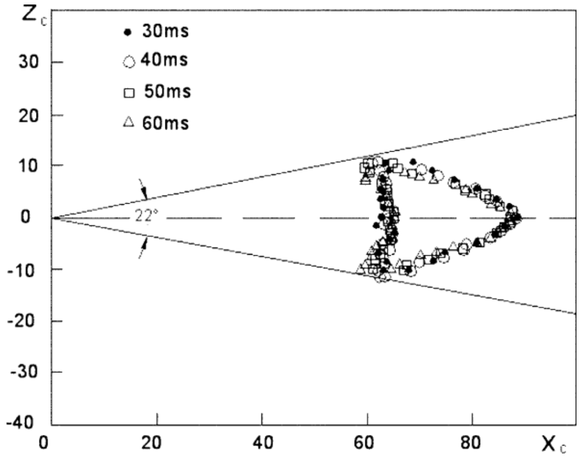

Fig. 6. Conical similarity of spots

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Conclusion

The spot propagation characteristics of an artificially generated turbulent spot have been studied in a laterally converging constant pressure flow. Although we have not studied the internal structure of the turbulent spot, the overall spot propagation characteristics are found to be similar to those in 2-D constant pressure flows.

Acknowledgement

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